520

VOLUME 80 SEPARATE No. 520

PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

OCTOBER, 1954

HYDROLOGY CHARACTERISTICS: CENTRAL AND SOUTHERN FLORIDA PROJECT

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IRRIGATION AND DRAINAGE
DIVISION

{Discussion open until February 1, 1955}

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Printed in the United States of America

Headquarters of the Society
33 W. 39th St.
New York 18, N. Y.

PRICE $0.50 PER COPY

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This paper was published at 1745 S. State Street, Ann Arbor, Mich., by the American Society of Civil Engineers. Editorial and General Offices are at 33 West Thirty-ninth Street, New York 18, N. Y.

HYDROLOGY CHARACTERISTICS CENTRAL AND SOUTHERN FLORIDA PROJECT

Angelo Tabita,[1] A.M., ASCE

SYNOPSIS

Hydrologic investigations within the area served by the Central and Southern Florida Project consider the behavior of water as it occurs in the atmosphere, on the surface of the ground, and underground. In connection with the planning and design of the water-control works contained in the project, the principal hydrologic factors of rainfall, run-off, evapo-transpiration, infiltration, and ground water storage are resolved to solve problems relating to the regulation, control, and utilization of water. This paper deals principally with climatic characteristics, the behavior of surface and ground water within the project area, the methods of collecting basic water-level and stream flow data, and the analysis and use of such data.

Description of Project Area

The general region embraced by the comprehensive plan for central and southern Florida lies in that part of the State south of the latitude of Cape Canaveral and the city of Orlando, and generally east of the ridge which divides the waters which flow into the Atlantic Ocean from those which reach the Gulf of Mexico. The individual drainage basins included in that area constitute, for all practical purposes, a single watershed since in most cases their waters intermingle during periods of heavy rainfall and their problems of water control and use, as well as their economic problems, are closely interrelated. The area includes some 15,000 square miles and its principal subdivisions are:

a. Upper St. Johns River Basin
b. Kissimmee River Basin
c. Lake Okeechobee
d. The Everglades
e. Lower east coast area

A map of the general region showing the principal subdivisions is shown on figure 1.

Upper St. Johns River Basin.

St. Johns River is one of the few streams in the United States which flows generally north. The upper St. Johns River Basin, considered to

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FIG. 1 CENTRAL AND SOUTHERN FLORIDA

be that area from Lake Harney south to the headwaters, contains about 2,500 square miles. The headwaters form in a flat area of lakes, marshes, and prairies, mostly in Indian River County; the area is separated from the saline Indian River by a low coastal ridge 3 to 10 miles wide and ranging up to elevation 30 feet.[2] That flat area varies from 22 feet to 24 feet in elevation, although some elevations up to 80 feet are found along the western ridge. Open water and the beginnings of the channel of St. Johns River appear first in the vicinity of Melbourne, thence, the river follows a tortuous channel northward, interrupted by a number of lakes until a more definite channel develops below Lake Harney. The uniformly flat lands of the entire area are without predominant slope and are generally made up of grassy prairies. The soil of the area is mostly sand and clay with some extensive muck lands, all of which is underlain by sedimentary deposits of limestone.

Kissimmee River Basin.

That part of the area designated Kissimmee River Basin includes its headwater lakes and those on the low, indeterminate divide between St. Johns and Kissimmee Rivers. The drainage area of Lake Istokpoga, the region known as Indian Prairie, and the basin of Fisheating Creek, as well as certain minor streams such as Taylor Creek, are also physically and economically a part of Kissimmee River Basin. The entire area of about 4,400 square miles drains into Lake Okeechobee from the north and northwest. The basin is bounded on the west by a fairly high, sandy ridge, where elevations reach 150 to 300 feet. That ridge separates Kissimmee River Basin from the Peace River Basin which drains to the Gulf of Mexico. On the east a low, poorly defined ridge about 1 to 4 miles wide separates Kissimmee River Basin from the headwater areas of St. Johns and St. Lucie Rivers. The entire Kissimmee River Basin and related areas are generally flat with a gentle slope southerly toward Lake Okeechobee. The basin is characterized by prairie lands interspersed with flat pinewood lands, swampy timber lands, pastures, and cultivated areas. Soils of the entire basin are largely sand and sandy loam, with some muck areas on top of clay and marl formations.

Lake Okeechobee.

Lake Okeechobee, which receives most of the waters which accumulate in Kissimmee River Basin and related areas, lies about 30 miles from the Atlantic coast and 60 miles from the Gulf of Mexico. It is a large, roughly circular, fresh-water lake about 730 square miles in area. Much of it is very shallow and the deepest parts extend only to about sea level. In its former natural state Lake Okeechobee had no well-defined outlet; its rising waters would spread over the vast Everglades area to the south, or spill slowly into the flat areas west of the lake and find their way to Caloosahatchee River, or escape by seepage and some overland flow to Allapattah, Hungryland, and Loxahatchee sloughs to the east. Under present conditions, Lake Okeechobee has been impounded by levees which block escape of its waters into the Everglades; its present outlets are St. Lucie Canal and Caloosahatchee

2. All stages and elevations throughout this paper refer to mean sea level datum.

River.

The Everglades.

In its original state the region now known as the Everglades was a vast solitude of sawgrass and water and was aptly termed by its Indian inhabitants the "Pa-hay-okee" or "grassy water." That grassy marsh is about 40 miles wide on the average and extends about 100 miles from Lake Okeechobee to the sea at the southern end of Florida; arms of the Everglades also extend partly around the eastern and western shores of Lake Okeechobee. The area lies in a trough of sedimentary limerock and is bordered on the east by a narrow coastal ridge which attains elevations up to 13 feet. On the west, the Everglades area is bounded by sandy ground which rises to an elevation of about 25 feet and includes the areas known as "Devil's Garden" and "Big Cypress Swamp."

Lower east coast area.

The coastal ridge is a strip of sandy land 5 to 10 miles wide which forms the eastern border of the Everglades. It is the most populous region of the area under consideration—the majority of that area lying in Palm Beach, Broward, and Dade Counties, where the cities of West Palm Beach, Fort Lauderdale, and Miami are situated.

Run-Off and Stream Flow

The generally flat topography of the area, its vegetation, and the absorptive nature of its soils combine to produce very low run-off characteristics. Long, continued rains gradually saturate the soils and fill the natural lakes and sloughs. Natural stream channels, such as Kissimmee River, are inadequate to carry off the water accumulated over large level areas. The water spreads over the lower lands in a thin sheet and moves slowly as overland flow in the direction of the prevailing slope. In the areas where the slope is indeterminate, the direction of winds and differences in rainfall distribution will change the direction of drainage. Artificial drainage outlets, pumping, and dikes are means used to accelerate run-off. High flows usually occur during the period June to December and last for several months. Direction of drainage in the headwaters of St. Johns River is largely indeterminate and differences in rainfall over parts of the area, as well as the direction of winds divert flows either eastward toward Kissimmee River or southward toward St. Lucie River. However, in the area below Lake Poinsett, numerous small tributary streams cause the fast accumulation of floodwaters in the main stream. The extensive marsh prairies that cover most of the upper reaches of the river valley with the abundant growth of various grasses, the large number of lakes, and the flat slope of the valley combine to hold the run-off in storage. The marsh prairies are inundated each year—usually remaining under water for several months. Major flooding occurs about once in six years inundating areas up to about 1,700 square miles. At the Christmas gaging station, where St. Johns River drains an area of 1,420 square miles, the maximum observed peak discharge was 10,700 cubic feet a second, occurring in October, 1947. The mean annual discharge at that station

is 1,350 cubic feet a second; there have been times when there was little or no flow.

The distribution of run-off in the upper basin of the Kissimmee is influenced by storage in the chain of large lakes, which, with the interconnecting canals, make up the main headwaters tributary to Kissimmee River. There is an aggregate of about 200 square miles of lake surfaces in the upper basin, or about 10 per cent of its area. The run-off leaving the upper basin is measured at a gaging station on Kissimmee River at the outlet of Lake Kissimmee (drainage area = 1,850 square miles), where records have been collected since 1930. The normal annual run-off of the area above that point is about 7.0 inches. Normal monthly run-off ranges from a minimum of about 0.4 inch, usually occurring in May, to about 0.8 inch, usually occurring in October. The maximum observed discharge was 8,820 cubic feet a second, occurring in October, 1948. The mean annual discharge is about 1,210 cubic feet a second; flows as low as 460 cubic feet a second, have been observed.

The lower basin of the Kissimmee comprises an area of about 1,450 square miles. The major portion includes Kissimmee River proper, which begins at the outlet of Lake Kissimmee and flows through a nearly flat valley. During low water conditions, the river follows a meandering—but clearly defined—channel; however, at flood stages it inundates several miles on each side of the channel. The normal fall from Lake Kissimmee (which lies at an elevation of about 52 feet) to Lake Okeechobee is 30 feet in a distance of about 98 miles. Lakes are few as are well-defined tributary channels. The western half of the lower basin drains an area of about 700 square miles through Arbuckle Creek, Lake Istokpoga, and Istokpoga Canal into Kissimmee River at a point of nearly 50 miles above its mouth. That portion of the basin contains about 30 lakes having an aggregate area of about 100 square miles, or 14 per cent of the lower Kissimmee area. Run-off measured at the gaging station near the town of Okeechobee (drainage area = 3,260 square miles), averages about 1,980 cubic feet a second annually, or about 8.3 inches over the basin. A minimum flow of 231 cubic feet a second has been observed and a discharge as high as 17,400 cubic feet a second, occurred during October, 1948. During the 1928 hurricane, the maximum discharge at the Okeechobee gaging stations may have been as high as 20,000 cubic feet a second. Average monthly run-off varies from a low of about 0.5 inch in May to a high of about 1.0 inch in September and October. Flooding in the basin is a common occurrence, and major floods have occurred at a frequency of about one in five years. The estimated area in the Kissimmee River Basin and related areas inundated in the 1947 flood was about 1,000 square miles. Floodwaters remain on the land from one to six months.

Of all the drainage divisions in the central and southern Florida area, Fisheating Creek Basin more nearly approaches the characteristic of flashy or rapid run-off. Draining a relatively high sandy area of almost 300 square miles, the maximum observed discharge at Palmdale was 31,400 cubic feet a second, which occurred in October, 1951. Peak discharges of that magnitude have never been approached anywhere in the central and southern Florida area. Normally, the annual run-off in the basin averages about 247 cubic feet a second, or 5 inches over the

basin.

The run-off characteristics of the Lake Okeechobee-upper Everglades area differ from those of the area to the north and are unique. The level lands of the Everglades and all the towns lying generally south of the lake perimeter are subject to destructive flooding by continued heavy rains over the area. The area is also subject to flooding by overland flow of waters accumulating on wild lands lying east of the lake and south of St. Lucie Canal, and by overland flow from the west. Water storage in Lake Okeechobee, although comparatively shallow, is relatively large because of its great surface area. Figure 2 illustrates graphically the relation of lake area and capacity with stage. Lake stages have ranged from a low of 10.3 feet to as high as 20.2 feet. Figure 3 shows the relative occurrence of designated stages in the lake during the period of record. At present, the lake is regulated insofar as possible between elevations 12.5 and 15.5 feet. By June 1, the beginning of the hurricane season, the lake is drawn down to elevation 13 feet; and as hurricane incidence decreases, the lake is allowed to rise and regulatory discharges through St. Lucie Canal and Caloosahatchee River are made only to insure that elevations would not exceed 14 feet by October 15; 15 feet by October 31, and 15.5 feet by March 31.

Run-off from the Everglades area south of the lake is by way of four principal arterial canals connecting Lake Okeechobee with the Atlantic Ocean: West Palm Beach Canal, Hillsboro Canal, North New River Canal, and Miami Canal. Another—Tamiami Canal—flows from a summit both east and west, draining an area west of Miami. The other arterial canals are comparatively short in length, flow generally to the east, and serve to drain the coastal areas. The present characteristics of run-off from the Everglades are greatly changed from the conditions which existed prior to the extensive reclamation activities in the Everglades during the period 1905 to 1927. Under natural conditions, the waters of Lake Okeechobee would rise over the southern rim of the lake, push through the dense growth of custard-apple and other growth which formed that rim, and move slowly southward through the dense sawgrass marsh. There, waters would mingle with the tremendous amount of rain water standing on the flat expanse of the Everglades and flow slowly through the grass and other vegetation to escape eastward through a few small rivers which flowed through the east coast barrier ridge, or to pass eventually to the sea through the marshes and tangled mangrove thickets which mark the southern tip of the Florida peninsula. Total run-off is now greater since water stands on the surface of the "Glades" shorter periods of time, furnishing less opportunity for evaporation and transpiration losses. Normal annual run-off from the Everglades area averages about 10 inches, most of which finds its way to the Atlantic Ocean. About 15 per cent of that run-off flows across Tamiami Trail into the Everglades National Park area. The estimated annual net flow from the Everglades area (about 4,500 square miles), varied from about 3.7 inches in 1944 to about 31.2 inches in 1947. The records available for the area, and upon which the above run-off values are based, run from 1940 to date. From a standpoint of duration and areal extent, the magnitude of the 1947 flood in the Everglades area has no equal as far as is known. It is estimated that about 7,497,000

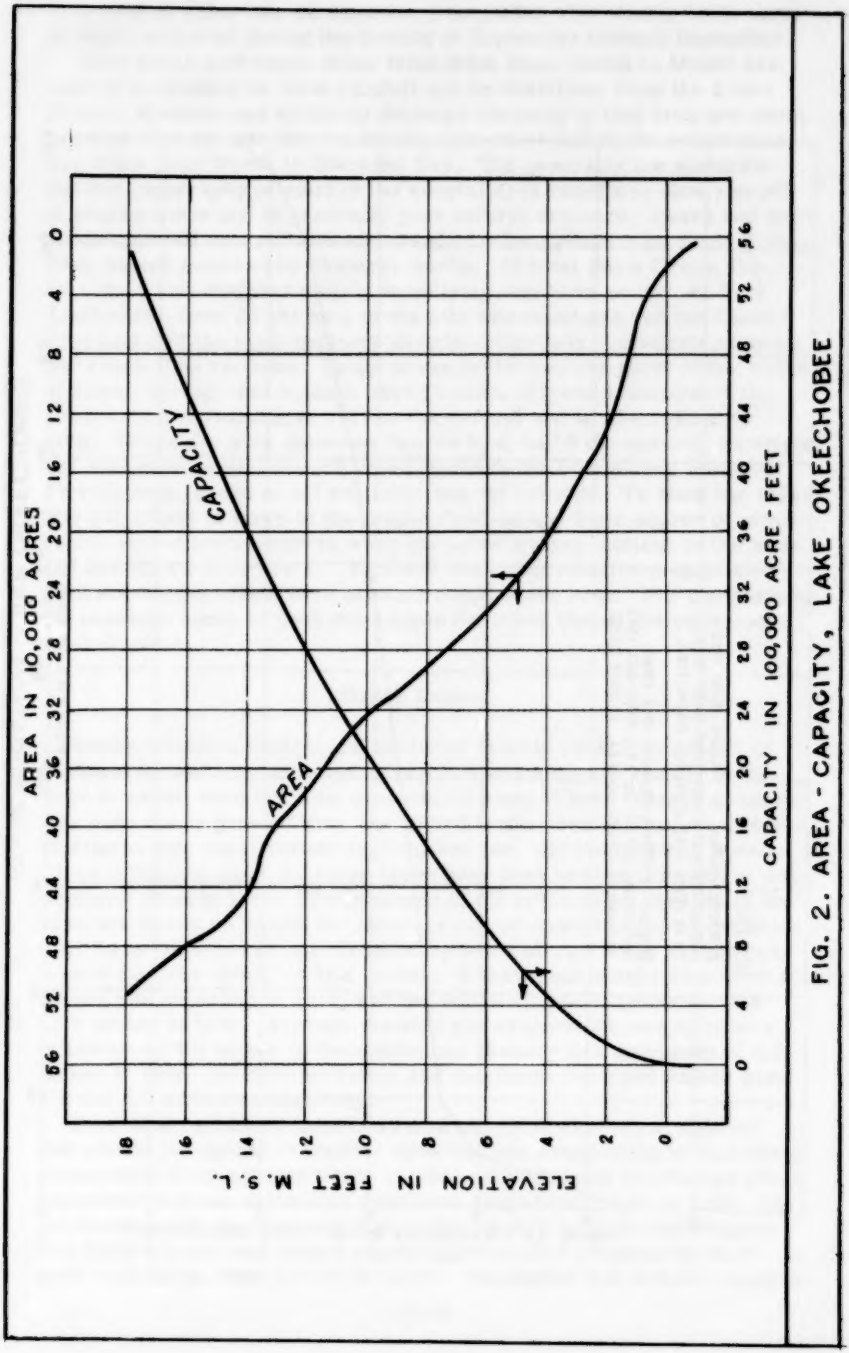


FIG. 2. AREA - CAPACITY, LAKE OKEECHOBEE

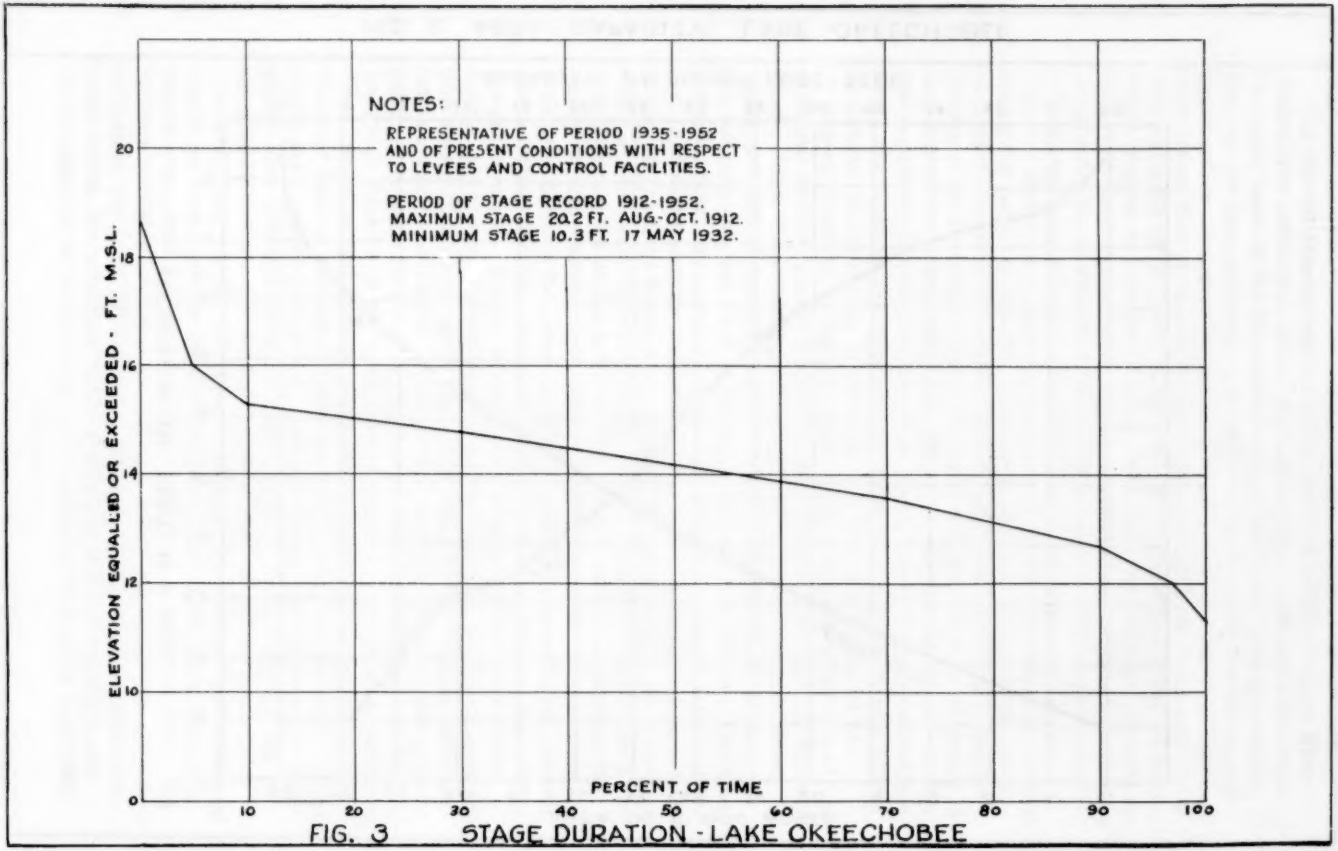


FIG. 3 STAGE DURATION - LAKE OKEECHOBEE

acre-feet of water ran off from the Everglades area during 1947, most of which occurred during the months of September through December.

Most urban east coast areas from West Palm Beach to Miami are subject to flooding by local rainfall and by overflows from the Everglades. Streams and artificial drainage channels in that area are short and flow directly into the coastal lagoons which follow the entire coastline from Lake Worth to Biscayne Bay. The generally low elevation and flat topography of most of the coastal area results in slow run-off of excess water and in generally poor natural drainage. Heavy and prolonged rainfall accumulates and stands for long periods on much of the land, unless removed by drainage works. At West Palm Beach, the 1947 flood was confined largely to outlying suburban areas. At Fort Lauderdale, over 30 per cent of the city was inundated and the flooded area included the main business district, railroads, industrial sections, and residential sections. Large areas in the western parts of the cities of Miami Springs and Hialeah were flooded. Figure 4 illustrates the areal extent of flooding in 1947 in the central and southern Florida area. There are also shown on figures 5, 6, and 7 the normal, minimum, and maximum annual run-off experienced in the central and southern Florida area, based on all available run-off records. To show the relative magnitude of flows in the major streams and their degree of occurrence, flow-duration curves were prepared for key stations in the area and are shown on figure 8. Figure 9 shows the relative magnitude of peak discharges which have been recorded in the area. For comparison, the envelope curve of peak discharges for other United States streams is also shown.

Water Losses

Water losses in central and southern Florida consist primarily of evaporation and transpiration. Evaporation losses are readily measured in small, open tanks or evaporation pans. Three types of evaporation pans are in general use: the United States Weather Bureau Class A ventilated pan, the Colorado-type sunken pan, and the Weather Bureau Class A floating pan. All three types have been used in the central and southern Florida area. The locations of all evaporation stations in the area are shown on figure 10. Average annual observed pan evaporation over Lake Okeechobee, as recorded by five Colorado-type sunken pans around the lake shore, is 55.6 inches. A maximum evaporation of 67.6 inches was recorded in 1919, and the minimum pan evaporation was 44.2 inches in 1925. Average monthly pan evaporation ranges from a minimum of 3.0 inches in December and January to a maximum of 6.3 inches in May. Monthly minimum and maximum recorded values were 1.8 and 9.0 inches respectively.

Several experiments have been made to determine the coefficient that should be applied to convert observed pan evaporation to equivalent evaporation from an open water surface. Coefficients determined from experiments made in the arid west have ranged from 0.63 to 1.00. Experiments made in other sections of the country indicate that evaporation from a large tank should closely approximate evaporation from ponds and large, open bodies of water. The United States Soil Conserva-

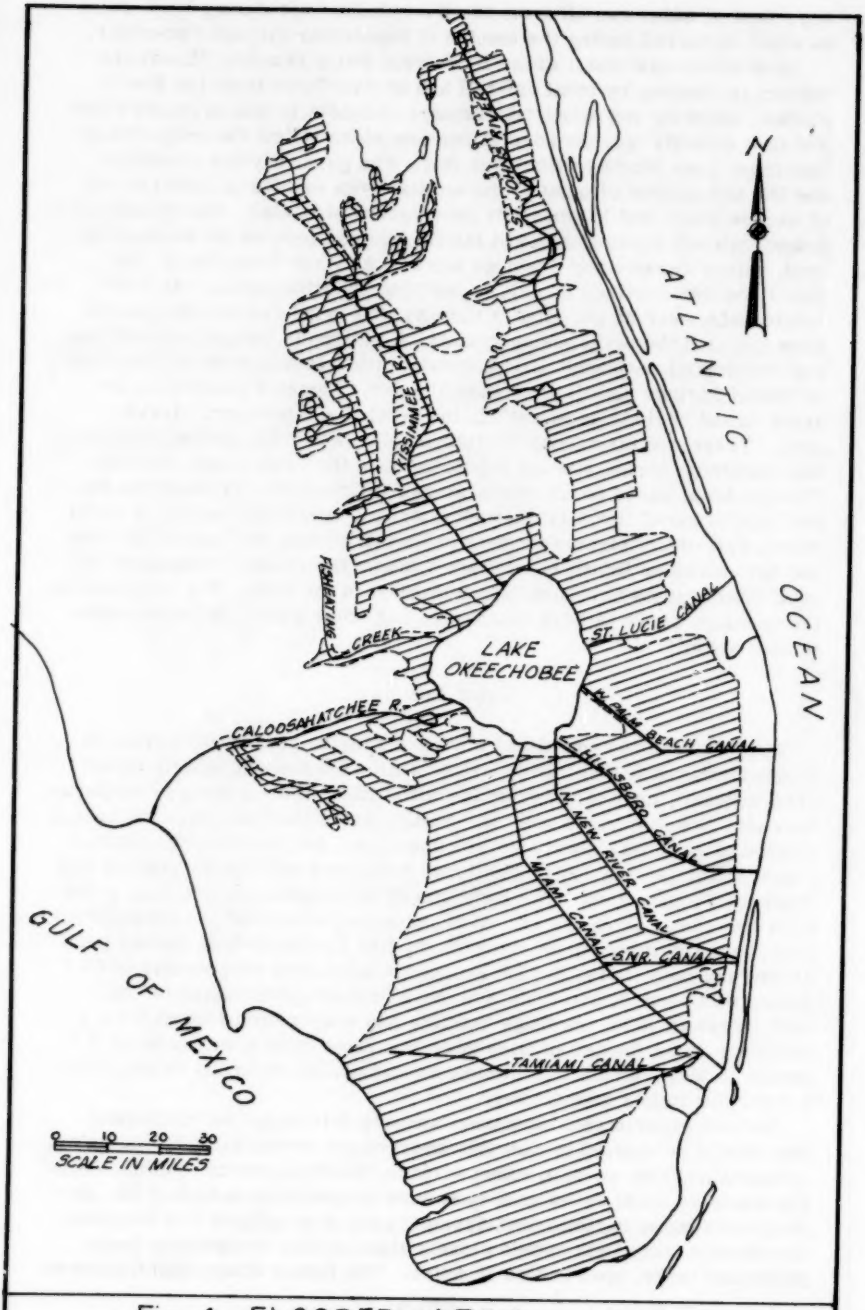


Fig. 4 FLOODED AREA - 1947

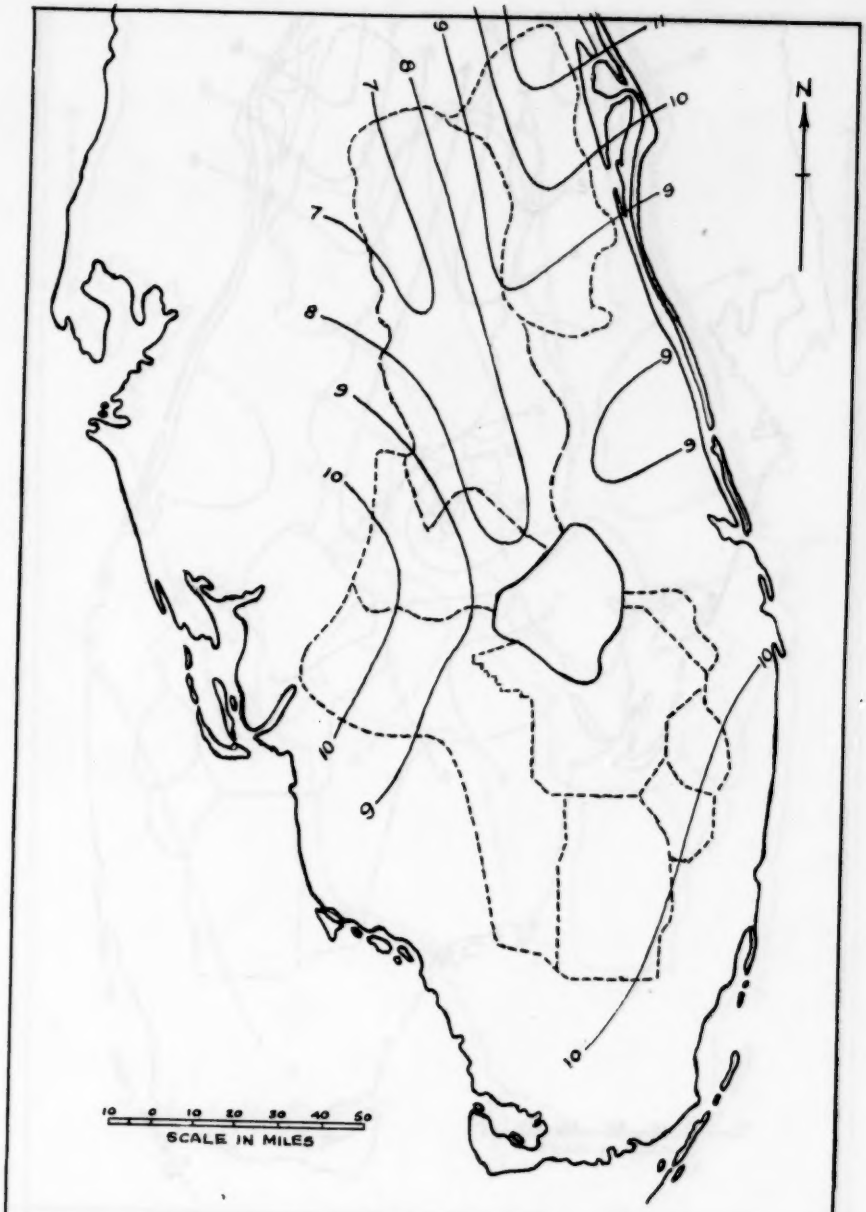


FIG. 5 NORMAL ANNUAL RUN-OFF IN INCHES.

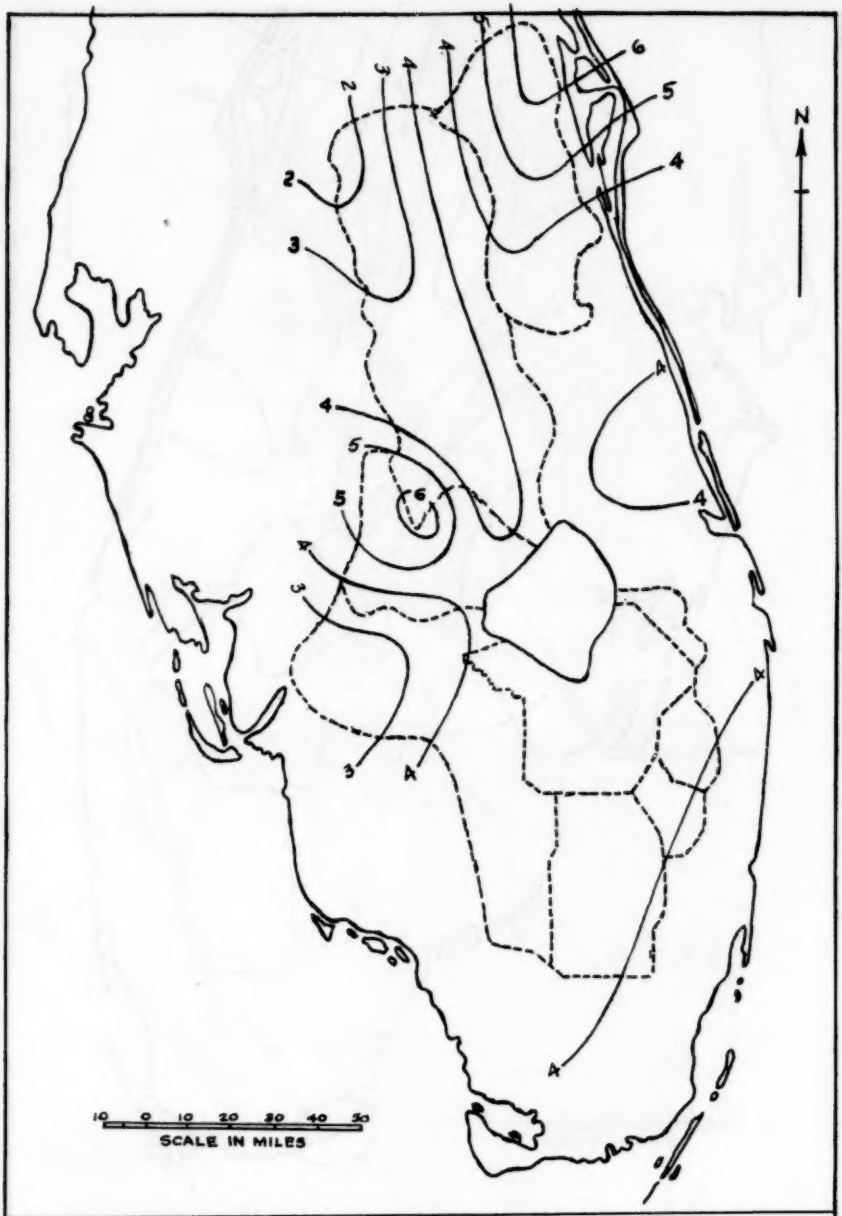


FIG. 6. MINIMUM ANNUAL RUN-OFF IN INCHES.

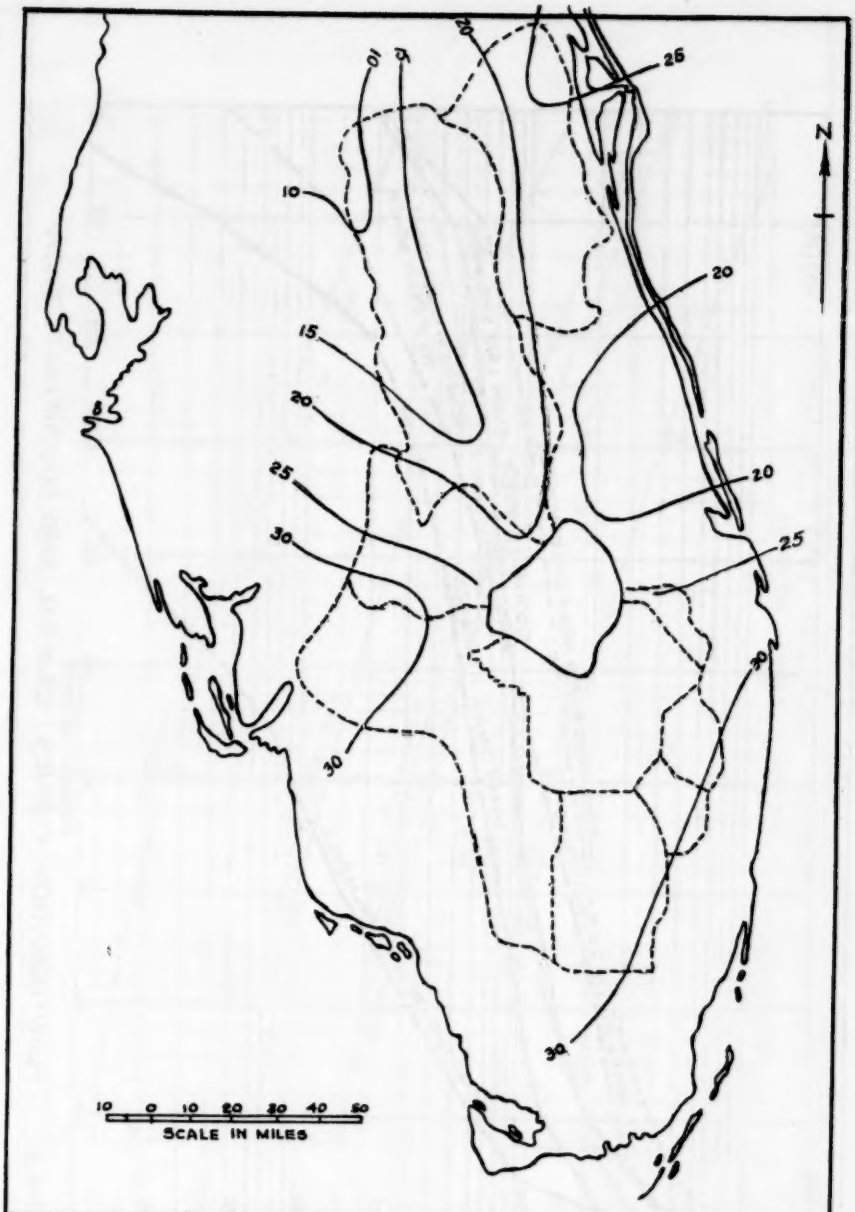


FIG.7. MAXIMUM ANNUAL RUN-OFF IN INCHES.

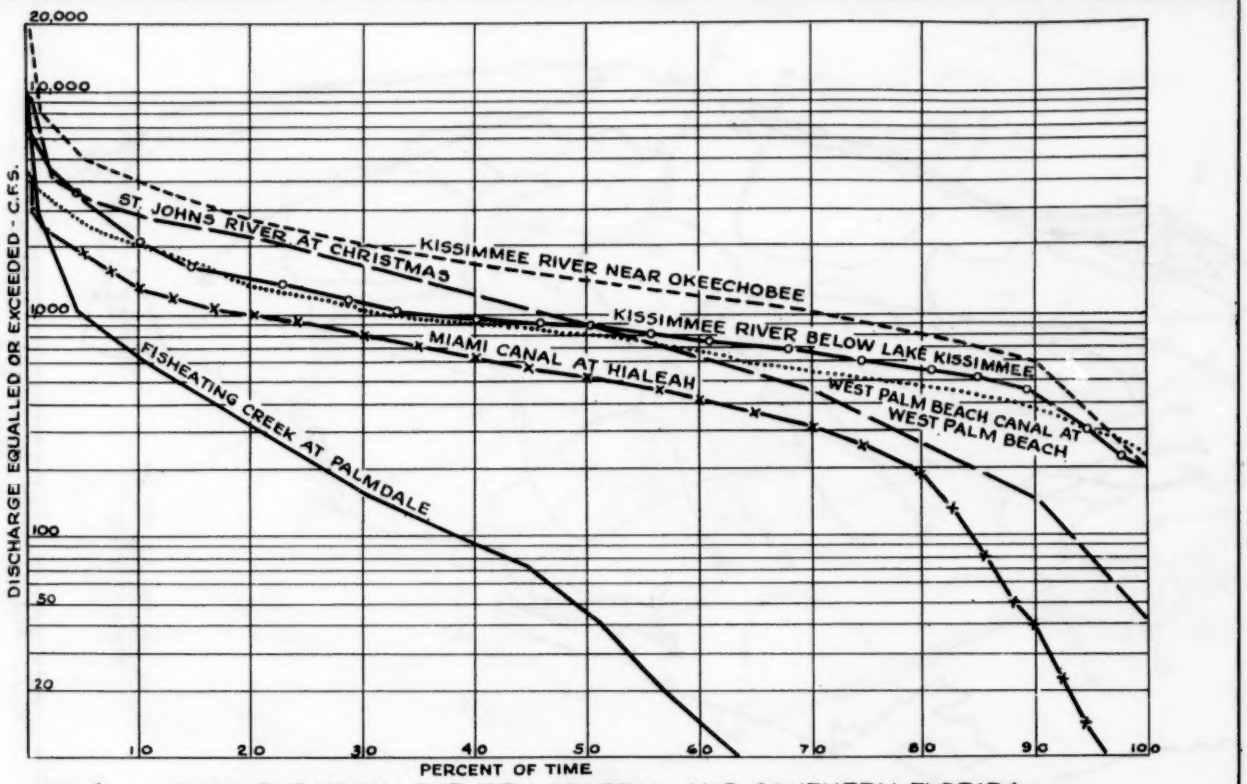


FIG. 8 FLOW-DURATION CURVES - CENTRAL AND SOUTHERN FLORIDA

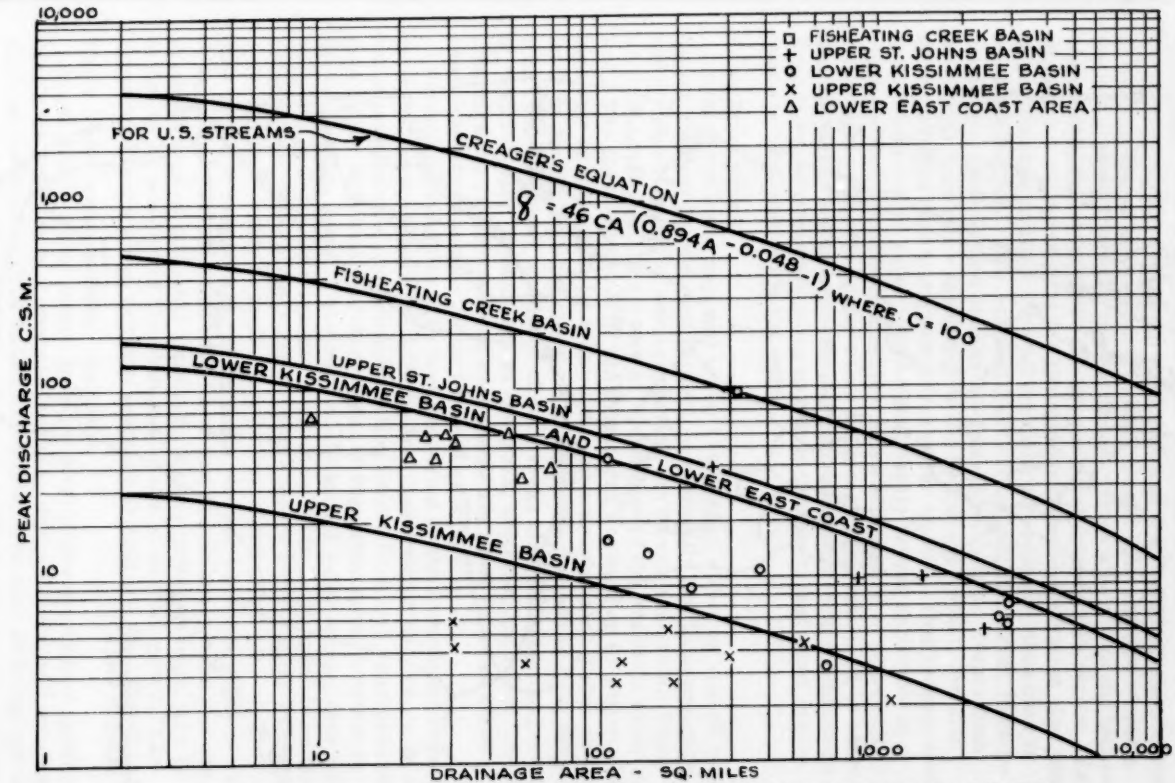


FIG. 9. PEAK DISCHARGES - CENTRAL AND SOUTHERN FLORIDA

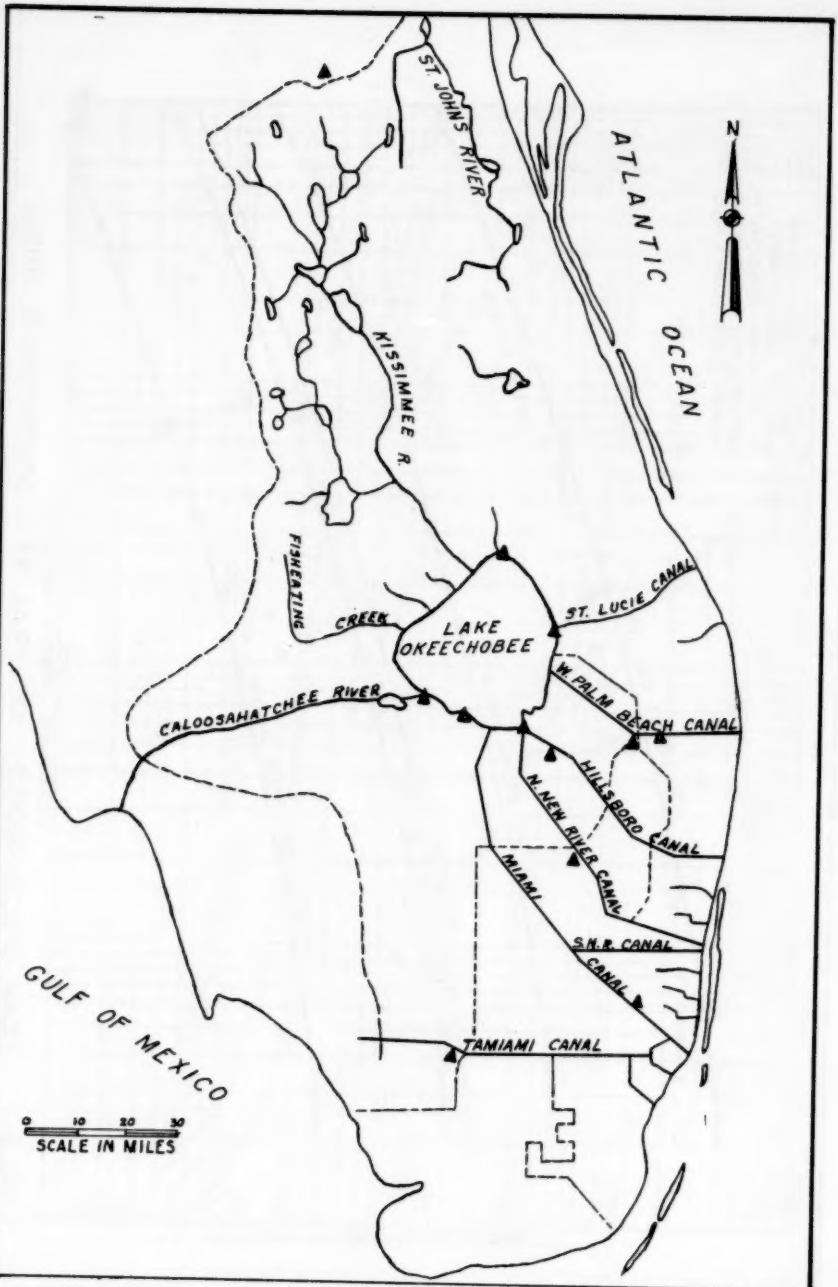


Fig. 10 EVAPORATION STATIONS

tion Service has conducted a continuing experiment at the Everglades Experiment Station to determine the coefficient for application to observed evaporation from a Weather Bureau Class A pan to convert to evaporation from a large steel tank. The conclusion reached from that 5-year experiment is that the coefficients as derived from experiments in western states for Weather Bureau Class A pans are considerably lower for south Florida. The coefficient varies widely with the season of the year, averaging 0.884 for the period of comparative record. Less complete investigations at the Everglades Experiment Station also point to a coefficient of about 0.95 for the Colorado-type pan when used in southern Florida. That range of coefficients has, in general, been indicated by water-budget studies for Lake Okeechobee. Evaporation rates have been more important in the hydrologic cycle in the arid western states than in regions with greater rainfall. Coefficients developed from western experiments would hardly appear applicable to a region of widely different characteristics with regard to practically every known climatic factor which influences evaporation. It is believed that the higher indicated coefficient values derived from the southern Florida experiments are more nearly applicable to that same region than are those derived in the west.

Everglades area.

Most of the water supplied to the Everglades, either by run-off from higher lands or from direct rainfall, is eventually lost by evaporation and transpiration or by seepage through the porous substrata. Under existing conditions, an average of 90 per cent of the available water is lost. The characteristics of the Everglades are such as to promote the high rate of water loss by evaporation and transpiration. Water accumulates in the flat, shallow marshes, provided ideal conditions for evaporation. The semi-wet condition of such areas also promotes the growth of "water-loving" plants such as sawgrass, eelgrass, and tules. The transpiration requirements of such plants are great in areas where conditions are favorable for that type of growth.

Several experiments have been conducted by the Everglades Experiment Station in cooperation with the Soil Conservation Service, in an attempt to determine evapo-transpiration losses from cultivated grasses, sugarcane, sawgrass, and other types of vegetative cover common to the Everglades area. A summary of the annual water losses, determined in two of those experiments, is given in Table 1. In order to relate results from those experiments to water losses for the upper Everglades area, it is necessary to apply a coefficient which would correct for differences in exposure to wind and sun, and for change in depth of water table. Other investigators have found that the consumptive use of water by plants such as tules and cattails in densely grown swamps, may be as low as 30 per cent of the consumptive use of similar growth in experimental tanks where extreme exposure to wind and sun exists.

Water losses under existing conditions.

In estimating water losses from the Everglades area under existing conditions, use has been made of available records of rainfall and run-off from the area south of Lake Okeechobee. The area of investigation is defined generally as the Everglades watershed, which is bounded on

the north by Lake Okeechobee levees; on the south by Tamiami Trail (US 41); on the east by the coastal discharge-gaging station on each of the canals involved; and on the west by the low drainage divide extending southward from Moore Haven to Tamiami Trail near Monroe. Simultaneous records of rainfall and run-off have been maintained since the latter part of 1939. Weighted monthly averages of rainfall were determined by Thiessen's method, based on records obtained at Weather Bureau stations in and adjacent to the area. Water entering the area from the lake was converted to inches and added to computed rainfall values to determine the total depth of water entering the area. Run-off is equal to the total volume of water discharged from the area by (1) the four major agricultural canals, both into Lake Okeechobee and to the Atlantic Ocean, (2) the four minor coastal canals, and (3) the outlets through Tamiami Trail. Run-off from the area is retarded by the relatively flat slopes and by heavy vegetation. For example, rainfall from a major storm period (such as occurred in the fall of 1947) affected discharge from the major canals and Tamiami Trail outlets for about 5 months. In order to estimate monthly or annual water losses for the area, it was necessary to estimate the amount of water in temporary detention or storage within the area. A study of the combined discharge hydrographs for the entire area for all major wet periods showed that the recession side of the discharge hydrograph followed a regular pattern, and that the slope of the recession was indicative of the volume of storage in the area. The volume of discharge for any month during a recession period could likewise be related to the recession curve, so that a discharge-storage relation could be determined. A curve showing

TABLE 1

Summary of annual water losses, evapo-transpiration experiments

Year	Annual loss (inches)				Std. evap. pan	Rainfall inches	Average depth to water (inches)(1)
	Sugarcane	Sawgrass	Bare soil	Evap. large tank, open water			
1934	50.36	-	42.66	-	65.27	62.24	-21
1935	46.53	-	39.21	-	70.60	48.81	-19
1936	43.53	-	35.97	-	66.62	64.57	-16
1937	45.42	84.04	42.28	-	64.44	58.44	-13
1938	35.03(2)	67.85	-	-	65.79	40.99	-14
1946	-	95.50	-	55.91	63.30	70.94	-48
1947	-	83.06	-	52.85	57.64	84.68	∤ 4
1948	-	69.16	-	52.54	62.17	62.98	-20
1949	-	63.96	-	57.02	63.42	53.53	-38

NOTES: (1) ∤ = water surface above ground; - = water surface below ground.
(2) Covered with heavy mulch of cane trash during the year.

discharge-storage relation was derived from observed discharge data, and from that curve the amount of storage within the area was obtained by application of recorded monthly discharges. The total water loss from evaporation, transpiration, and seepage is equal to the difference between the depth of water entering the area and the run-off, adjusted for the effect of change in storage. By use of the above relationship, monthly water-loss estimates were obtained for the period January, 1940 through April, 1949. Those monthly water losses (in inches) averaged for the period 1940 to 1949 are as follows:

Jan.	1.68	May	4.21	Sept.	4.78
Feb.	1.51	June	6.16	Oct.	3.51
Mar.	2.10	July	6.77	Nov.	2.38
Apr.	2.71	Aug.	5.45	Dec.	1.68

Annual----------42.94

Relationships correlating monthly losses with rainfall and other meteorologic phenomena for the Everglades were vague and poorly defined. However, a definite relationship is found when water losses are plotted against rainfall on an annual basis. That relation is shown graphically on figure 11. There is an optimum water loss for the area corresponding to conditions for producing maximum evaporation and transpiration. Such conditions depend primarily on the occurrence of ample rainfall, or supply of sufficient water from available sources, to fully satisfy evapo-transpiration demands. Apparently such demands were fully satisfied during most of 1947, when the calendar-year loss amounted to about 47 inches—the maximum of record. Average annual rainfall over the Everglades area in 1940 and 1941, (about 60 and 63 inches respectively), was considerably less than rainfall in 1947 (about 80 inches); however, water losses for those 3 years were practically the same, indicating that conditions for optimum loss are satisfied by about 60 inches of rainfall. In support of the validity of the annual losses plotted on figure 11, reference is made to an article by Robert L. Lowery and Arthur F. Johnson, titled "Consumptive Use of Water for Agriculture," which was published in "Transactions of American Society Civil Engineers," Volume 107, 1942. Lowery and Johnson found that, for all areas of investigation within the United States, the consumptive use of water for agriculture is a function of the effective heat supplied by the sun during the growing season. The relationship is shown graphically on figure 12. Effective heat (expressed in day-degrees above 32° F), is plotted against consumptive use, or water losses (expressed in feet). On the basis of a year round growing season, annual values of effective heat were computed for the Everglades area. When those values are plotted against corresponding annual water losses, the points conform closely to the Lowery-Johnson relationship.

Kissimmee area.

Following the general procedure described above, an analysis was made of rainfall and run-off records available for the Kissimmee River Basin. Run-off records in the Kissimmee are available as far back as

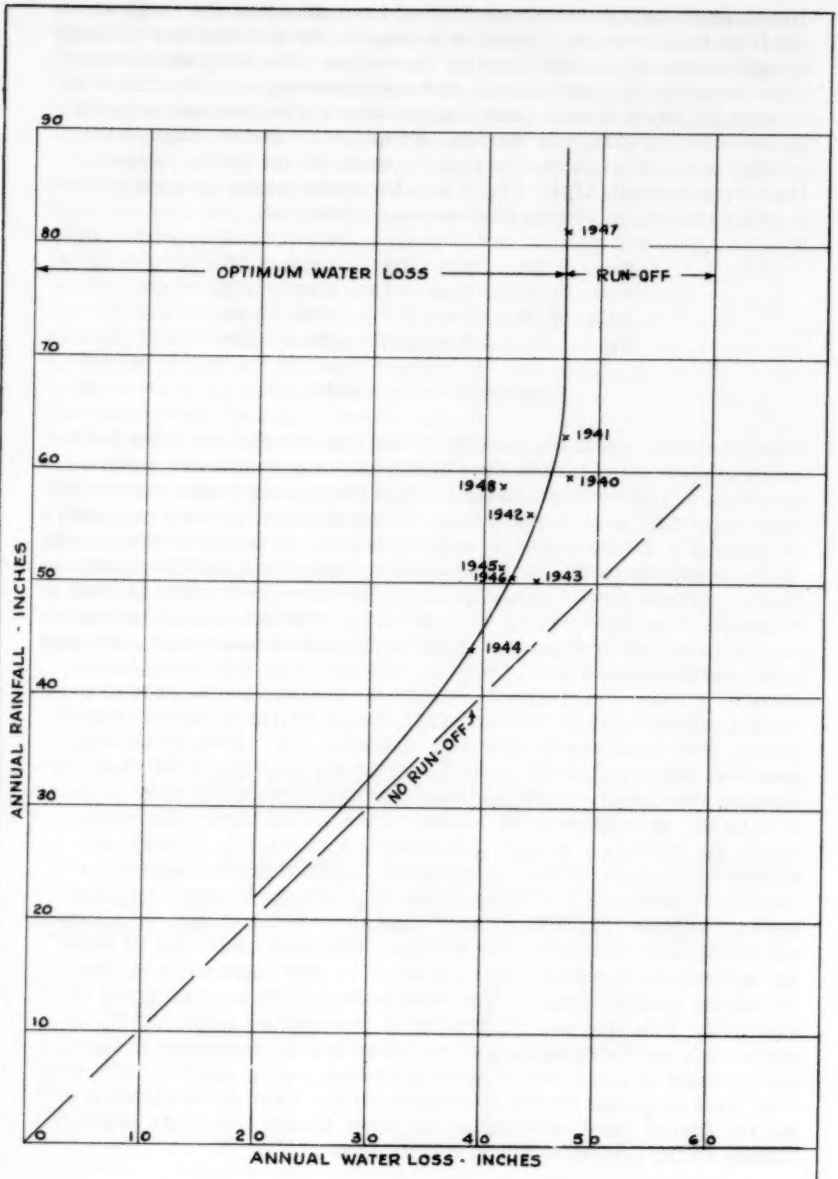


FIG. 11 RAINFALL-LOSS RELATION EVERGLADES AREA

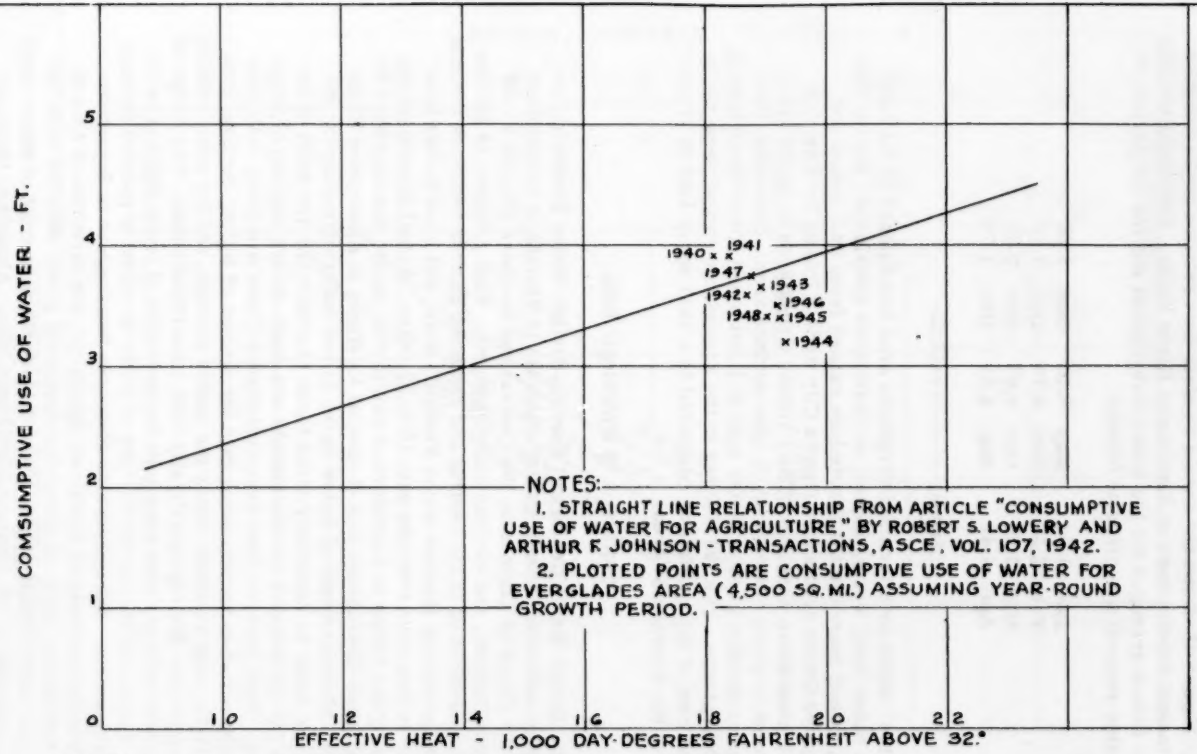


FIG. 12. CONSUMPTIVE USE OF WATER
EVERGLADES AREA

1931. Studies completed to date indicate the characteristic relation between annual rainfall and water losses as obtained for the Everglades area. Figure 13 shows the annual rainfall-loss relation representative of principal subdivisions of Kissimmee River Basin. Estimated monthly water losses averaged for the areas investigated and for the periods of available records are given as follows:

Jan.	1.94	May	5.45	Sept.	3.61
Feb.	2.56	June	4.79	Oct.	3.19
Mar.	3.60	July	4.67	Nov.	2.30
Apr.	4.43	Aug.	4.31	Dec.	1.74

Annual----------42.59

The 1947 water loss for the Everglades area (considered as the optimum water loss) was 47 inches, as heretofore mentioned. During that year, annual losses in the Kissimmee ranged from 44.8 inches for Josephine Creek area above Desota City to 51.2 inches for Cypress Creek area above Vineland. The Cypress Creek area is in the upper Kissimmee which contains much lake-surface area. Generally, there was considerably greater water loss in Kissimmee River Basin than in the Everglades. The 1947 losses in the Kissimmee ranged from 62 to 84 per cent of the rainfall as compared to a 1947 water loss of 57 per cent in the Everglades area.

Collection of Hydrologic Data

The United States Geological Survey, Surface Water Division, conducts an extensive stream-gaging program in Florida in cooperation with the Corps of Engineers, the Central and Southern Florida Flood Control District, and various other agencies. That program is particularly concentrated in the central and southern Florida region on account of the increasing interest which Federal, State, and local bodies have shown in that area over the past 12 to 15 years. Actual stream gaging made by the Corps of Engineers is confined to minor drainageways entering Lake Okeechobee and at special locations in Kissimmee River Basin. Measurements of inflow in the minor waterways entering the lake are made as necessary since those channels are dry most of the time. More frequent measurements are made during periods of large inflow. Such records have been collected and are now being collected in more detail to furnish basic data for studies of inflow, outflow, lake regulation, and available water for usable storage, and for other related investigations dealing specifically with Lake Okeechobee. The Corps of Engineers collects data weekly in the operation of pump stations on the lake shores and measures the flow of water in culverts passing through the lake levees During periods of severe flooding—as in September, 1947—measurements of elevation, discharge, and direction of flow of floodwaters are made at numerous important points over the area not equipped with regular gages. Figure 14 shows the extent of water-level gage coverage in the comprehensive plan area. Altogether there are about 160 water-level gages, most of which are automatic recording

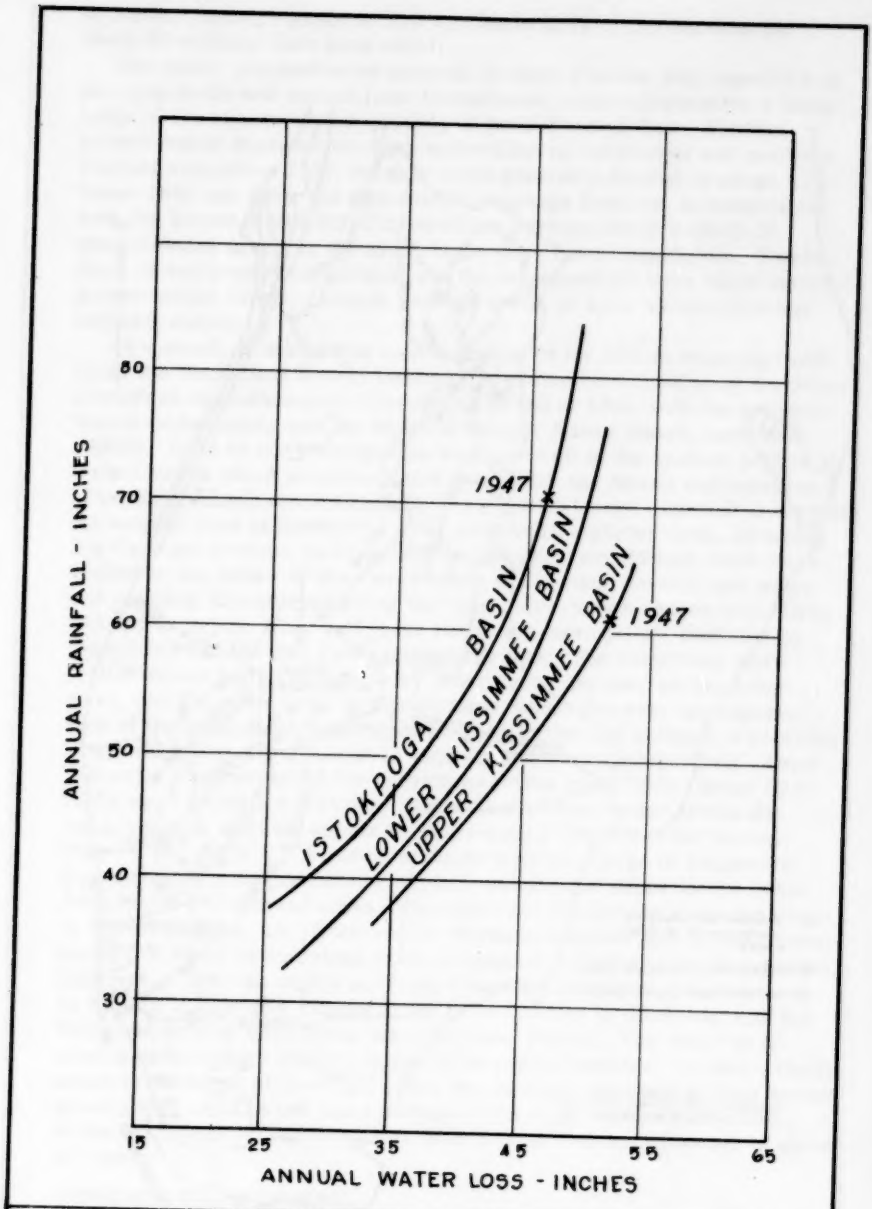


FIG. 13 RAINFALL - LOSS RELATION
KISSIMMEE AREA

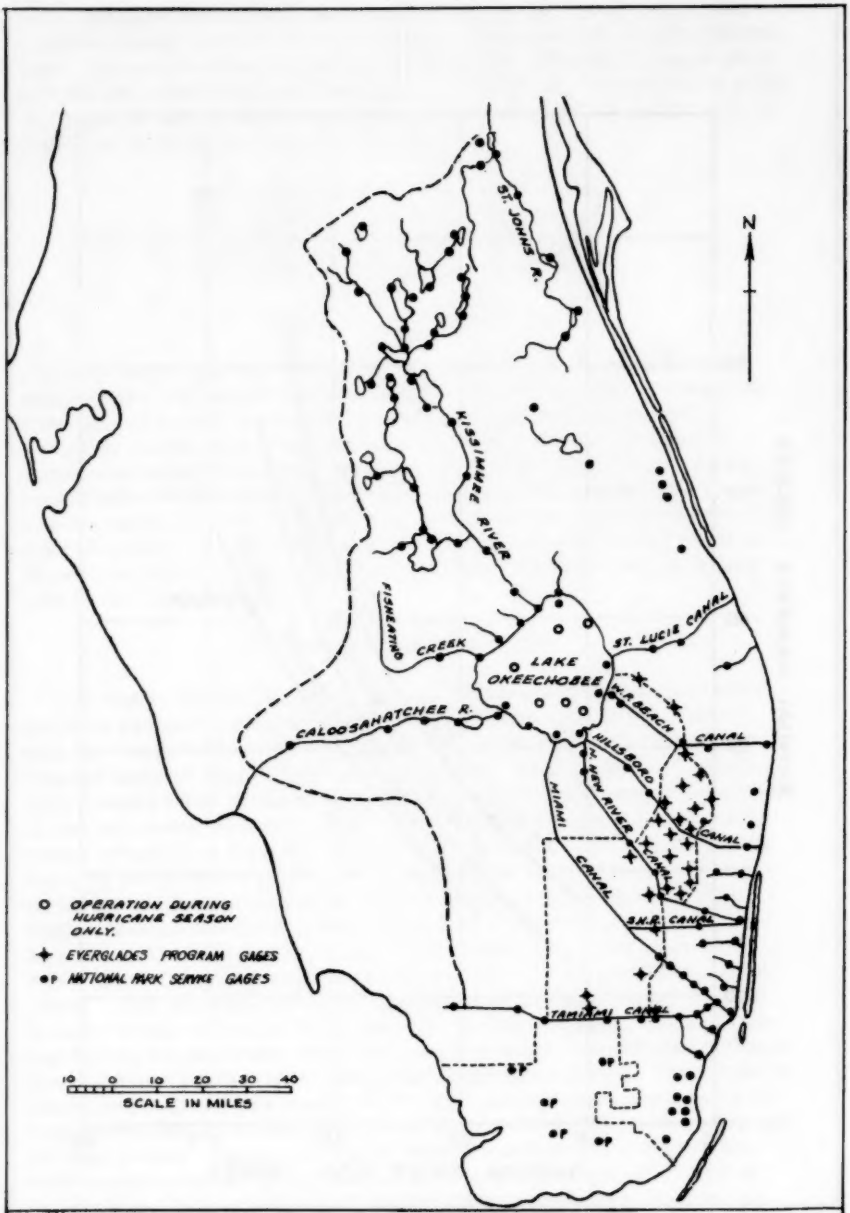


FIG 14. SURFACE-WATER GAGES

stations. Measurements of flow are made at 65 of the stations and about 30 stations have been rated.

The highly permeable formations in south Florida, and especially in the area south and east of Lake Okeechobee, makes imperative a knowledge of the character and quantity of ground-water flow. Various ground-water studies have been undertaken in the central and southern Florida area since 1932, but they were generally limited in scope. Between 1932 and 1934, the Everglades Drainage District, in cooperation with the United States Soil Conservation Service, made a study of ground-water levels in the muck lands near Lake Okeechobee. Twelve lines of wells were established and the relationships were noted between ground-water levels, rainfall, and the levels of Lake Okeechobee and adjacent canals.

As a result of salt-water contamination of the Miami municipal well field, the Geological Survey began an intensive investigation of the water resources of southeastern Florida in the fall of 1939, with the cooperation of Dade County and the cities of Miami, Miami Beach, and Coral Gables. Most of the investigation was centered in the eastern part of Dade County, which provides water supply for the Miami metropolitan area; but geologic and hydrologic investigations were extended to include the coastal area of Broward County and the Everglades area, including Big Cypress Swamp. In carrying out that program, 89 test wells were drilled in the area. Studies were made of the rock, fossils, and water and pumping characteristics of the bore holes, which ranged from 50 to 812 feet in depth. Thirty of those test wells were jointly installed by the Survey and the Soil Conservation Service. The remainder were drilled either by the Survey or by other agencies, such as the Army, Navy, and Farm Security Administration, under the over-all supervision of the Geological Survey. In addition to the test borings, a program of ground water observations in existing wells was inaugurated. About 350 wells were observed for varying intervals since 1939. Some 50 of those were recording stations. Records of ground-water levels for many of those stations appear in water-supply papers of the Survey. Some of the wells will be used to supplement the Corps of Engineers' gaging program for measuring surface and ground-water levels in the Everglades and coastal areas. The coverage of existing recorder wells is shown on figure 15. Examination of records shows that a considerable amount of water is contained in the formation underlying the Everglades. Such water is in the highly pervious Tamiami limestone, which occurs in shallow formations varying from 10 to 100 feet in thickness with the thickest portions lying along the coast near Miami. The water is of good quality, though highly colored from organic matter, and has a fairly uniform hardness of about 250 parts per million. The water table varies greatly with rainfall but has a definite slope in an easterly direction. In the vicinity of Miami the water table has an average elevation of about 2.5 feet.

Everglades gaging program.

Due to the lack of basic hydrologic data in the interior of the Everglades, the Corps of Engineers has undertaken, with the cooperation of the Geological Survey, an extensive program to obtain data necessary for a practical analysis of hydrologic characteristics of the Everglades

FIG. 15 GROUND-WATER RECORDING GAGES

area. The Everglades—under existing conditions—is a wide, shallow, heavily vegetated marsh with a very flat, general slope from north to south. The movement of water in the area is questionable. There is some indication that flow from the Everglades may be from the fringe area rather than through the sawgrass and other aquatic growth. There are no reliable data available on the water-surface elevations and slopes or precipitation within the interior of the Everglades. Data regarding water stages, water-surface slopes, water losses, wind-tide, and associated meteorologic characteristics will be required for the final design of conservation areas and outlet facilities and for the determination of suitable regulation or operation criteria in connection with the Central and Southern Florida Project.

The program primarily involves the collection and analysis of data on the behavior of surface water over that portion of the Everglades extending from the Hungryland slough area east of Lake Okeechobee, south to Tamiami Trail. The over-all area covered is roughly 1,500 square miles. However, the bulk of the gaging stations is located in the areas designated as conservation areas Nos. 1 and 2. In addition, supplementary data would be available from the Everglades National Park area as the result of a gaging program of the National Park Service. The over-all gaging program involves the collection of meteorologic, wind-tide, and water-level data and includes the following:

a. Continuous measurement of water levels in canals and natural drainage courses to establish water-surface gradients that can be associated with intermittent discharge measurements and to assure reasonably accurate estimates of surface inflow and outflow to and from the areas considered.

b. Continuous measurement of water levels within the study areas to define the water-surface contours over the entire area at a given instant.

c. Current-meter discharge measurements at selected stations located at or near the perimeter of the study areas.

d. Current-meter velocity measurements at selected points within the study areas.

e. Continuous rainfall measurements at a sufficient number of stations to establish fairly accurate isohyetal patterns.

f. Continuous measurement of atmospheric pressure, temperature, evaporation, humidity, and radiation at selected points within the study areas.

g. Continuous measurement of wind velocities and directions in or near the study areas in order to obtain an index to the wind pattern that may be used in estimating wind-tide effects on water levels.

In all, there are 32 gages which make up the special network (see figure 14). Five of those gages, which are the dual-recording type, are located in the Everglades National Park and are operated by the National Park Service.

The dual-recording stations which record levels of rainfall and surface water or ground water simultaneously on one chart are of special advantage in the Everglades. Those stations may go unattended for as long as 60 days, and in view of the very limited access into the "Glades," are most desirable. A typical installation is shown on figure 16.

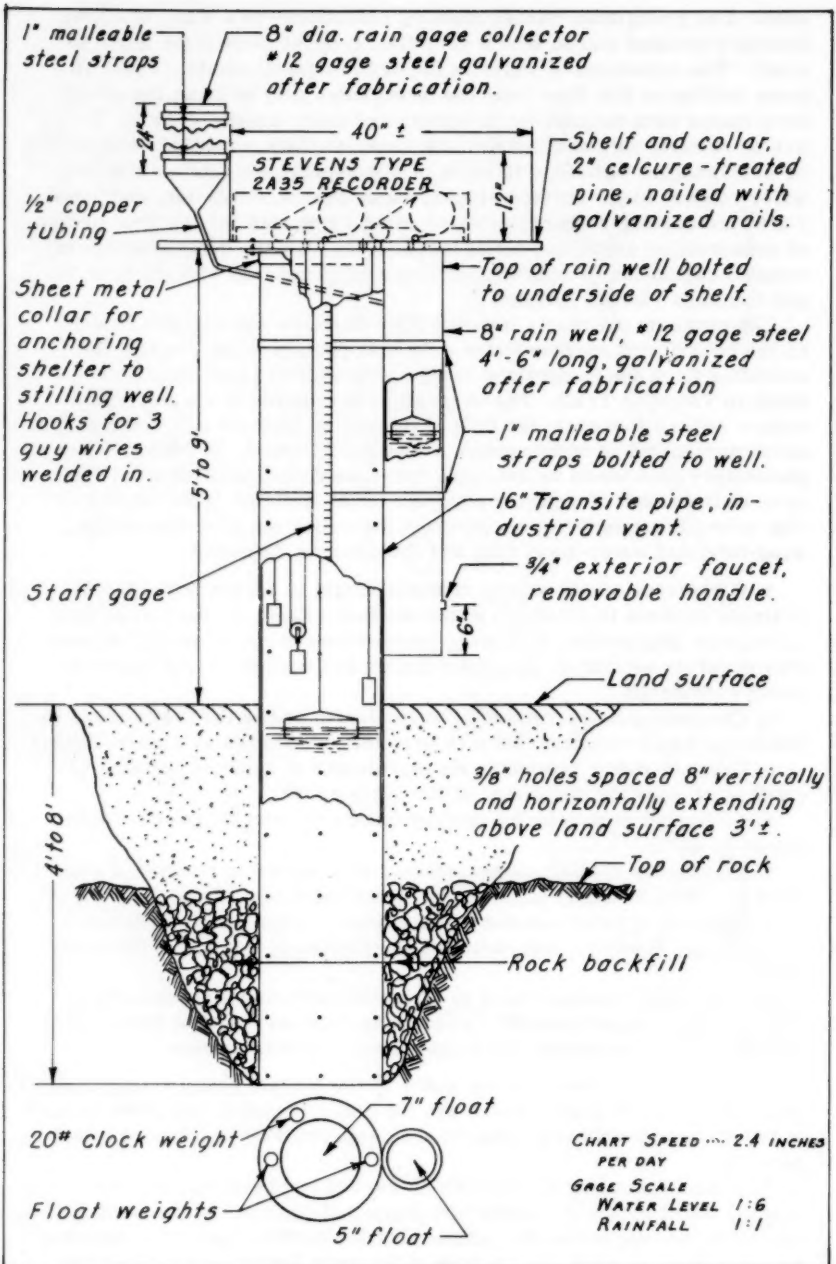

1" malleable steel straps
8" dia. rain gage collector #12 gage steel galvanized after fabrication.
2"
40" ±
STEVENS TYPE 2A35 RECORDER
12"
Shelf and collar, 2" celcure-treated pine, nailed with galvanized nails.
½" copper tubing
Top of rain well bolted to underside of shelf.
Sheet metal collar for anchoring shelter to stilling well. Hooks for 3 guy wires welded in.
8" rain well, #12 gage steel 4'-6" long, galvanized after fabrication
5' to 9'
1" malleable steel straps bolted to well.
16" Transite pipe, industrial vent.
¾" exterior faucet, removable handle.
Staff gage
6"
Land surface
⅜" holes spaced 8" vertically and horizontally extending above land surface 3' ±.
4' to 8'
Top of rock
Rock backfill
7" float
20# clock weight
Float weights
5" float
CHART SPEED — 2.4 INCHES PER DAY
GAGE SCALE
WATER LEVEL 1:6
RAINFALL 1:1

FIG.16 DUAL-RECORDER INSTALLATION

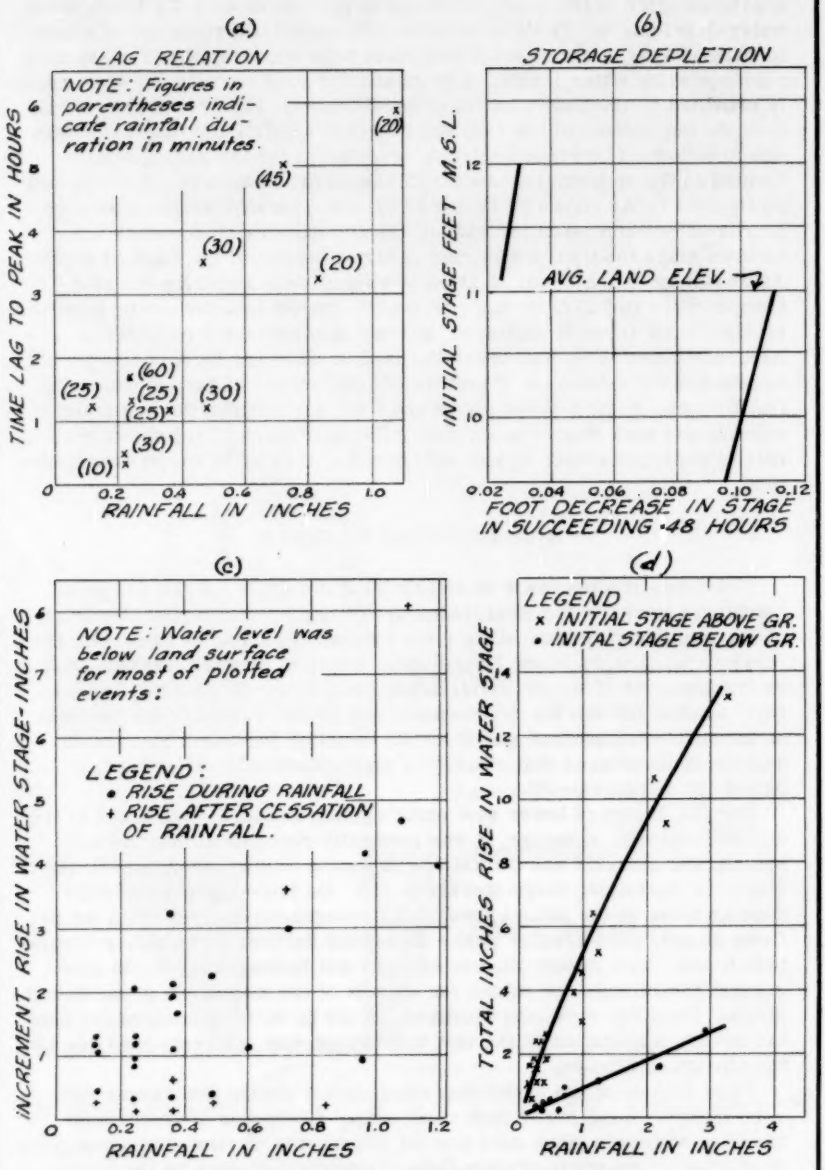
It may be of interest to present some preliminary data on hydrologic characteristics in the conservation area as indicated by the Everglades water-level gages. To determine the characteristic response of stages to water levels, a correlation was made between rainfall and changes in corresponding water levels. The means for such correlation were readily provided by the dual-recording installations. The correlation should indicate the portion of the rise attributed to rainfall and that which was due to inflow. The results of such correlation for the gaging station located in the approximate center of conservation area No. 2 are shown on figure 17. As shown by figure 17 (d) considerable water movement—or run-off—is indicated for each of the separate rainfall events considered since the total water rise is far in excess of the rainfall depth. As shown by figure 17 (c) an attempt was made to separate the rise from direct rainfall from the rise due to run-off into the area. However, no significant trend is indicated, at least for the events considered. Also, the water level was below the land surface for most of the plotted events and the relation is therefore characteristic of ground water fluctuations. Figure 17 (a) shows the time lag between the beginning of rainfall and peak stages at the gage site, and figure 17 (b) shows the rate of depletion either by run-off from the area or by evapo-transpiration.

Hydrologic Basis for Design

Hydrology studies made in determining the basis for the design of structural works in the Everglades area vary from accepted practices of determining flood run-off in river basins. Flooding is caused by the peculiar topography of the Everglades, a lack of natural drainage, and by inadequacies of the artificial drainage system. In general, hydrologic studies involve the determination of design rainfall over the area of interest, evaluation of water losses to obtain the effective rainfall, and the application of that rainfall to appropriate run-off criteria to obtain the design run-off.

For the design of lower east coast canals, recourse was made to the unit hydrograph. However, it was generally recognized that the unit hydrograph analysis has limitations in basins having streams with flat slopes or containing large storage areas. On flat-sloped waterways such as those in the Miami area, unit hydrographs derived from small flows usually have greater peaks than those derived from higher-magnitude flows. As a result, the use of such unit hydrographs would give greater peak discharge values for storms of the magnitude of the design storm. Since the resulting discharge would be on the conservative side for design, application of the unit hydrograph was not restricted due to the storage limitation.

Flow data on which to develop estimates of design discharges are very meager in the lower east coast area. Estimates of discharges based on available stage data are not dependable in view of the complexity of relating stages to stream flow. Construction work on the canals during the period of record, regulation by numerous local control structures, and tidal effect would preclude any fixed relation between stage and discharge. Continuous records of daily discharge are available for


(a)
LAG RELATION
NOTE: Figures in parentheses indicate rainfall duration in minutes.
TIME LAG TO PEAK IN HOURS
RAINFALL IN INCHES
(b)
STORAGE DEPLETION
AVG. LAND ELEV.
INITIAL STAGE FEET M.S.L.
FOOT DECREASE IN STAGE IN SUCCEEDING 48 HOURS
(c)
NOTE: Water level was below land surface for most of plotted events:
LEGEND:
• RISE DURING RAINFALL
+ RISE AFTER CESSATION OF RAINFALL.
INCREMENT RISE IN WATER STAGE-INCHES
RAINFALL IN INCHES
(d)
LEGEND
x INITIAL STAGE ABOVE GR.
• INITAL STAGE BELOW GR.
TOTAL INCHES RISE IN WATER STAGE
RAINFALL IN INCHES

RAINFALL-STAGE RELATIONS

NOTE: DATA FROM GAGING STATION 2-17

FIG. 17 WATER-LEVEL CHARACTERISTICS CONSERVATION AREA NO. 2

Miami Canal at Hialeah for the period 1940 to date, for Miami Canal at Pennsuco near Miami for the period 1940 to 1943, and for Cypress Creek (Pompano) Canal at Pompano Beach for the period 1940 to 1943. Those records were used principally as the basis for developing rainfall-run-off relationships. A number of unit hydrographs were derived from the records. Each of the observed hydrographs was resolved into its various components of flow. Generally, the outflow hydrographs at the gaging station would contain, in addition to the direct run-off from the local drainage area, local ground water or base flow, inseepage from adjacent areas and recession flow from channel and overbank storage. Estimates of ground-water flow were based on derived ground-water-recession curves and on stages observed at nearby wells. Also, ground-water discharge-rating curves were developed, based on the differential in head between the canal water surface and elevations at nearby ground-water wells. For the derived unit hydrographs, it was found that the peak of the ground-water flow occurred from 3 to 7 days after the start of rainfall excess, depending on the duration and volume of rainfall. The peak rate of ground-water discharge will occur when the ground-water gradient, as indicated by the canal stages and ground-water well elevations, is a maximum. To ascertain the validity of the unit hydrograph, a reproduction of the 1947 flood was made for Miami Canal at Hialeah. That reproduction is shown on figure 18. Ground-water discharges were estimated by means of the ground-water rating curve and the surface component of flow by the unit hydrograph. It will be noted that up to the peak and for a few days later, the reproduction is fairly reasonable. On the descending side, the volume of the observed hydrograph is greatly in excess of that of the computed hydrograph. However, subsequent to the peak of local area run-off, large quantities of water entered the area from the west and northwest, and the latter portion of the observed hydrograph shows that run-off. From the derived unit hydrographs, lag and other factors characteristic of run-off in the lower east coast area were determined.

The computed unit hydrographs used to determine design flows for the major canals were based on synthetic relations developed by F. F. Snyder, in his paper, "Synthetic Unit Graphs," Trans. American Geophysical Union, Part I, 1938, (pp. 447-454). The basic equations evolved by Snyder were modified by factors characteristic of run-off and terrain in the lower east coast area. Figure 18 shows the lag and discharge relationships based on data obtained from the natural unit hydrographs described above. Supplemental lag data for other canals in the lower east coast area were obtained from the natural unit hydrographs described above. All synthetic constants were derived from unit hydrographs converted to the same unit rainfall duration. As indicated by the lag relationship in figure 19. Snyder's lag formula $t_p = C_t\ (LL_{ca})^{0.3}$ was modified to $t_p = 15.4 \left(\frac{LL_{ca}}{\sqrt{S}}\right)^{0.124}$ where L and L_{ca} are, respectively, length of the stream or water course and length of stream to center of area, in miles. The slope S used herein is the basin slope. However, in several instances, owing to the extremely flat terrain and storage areas, the slope of the water surface

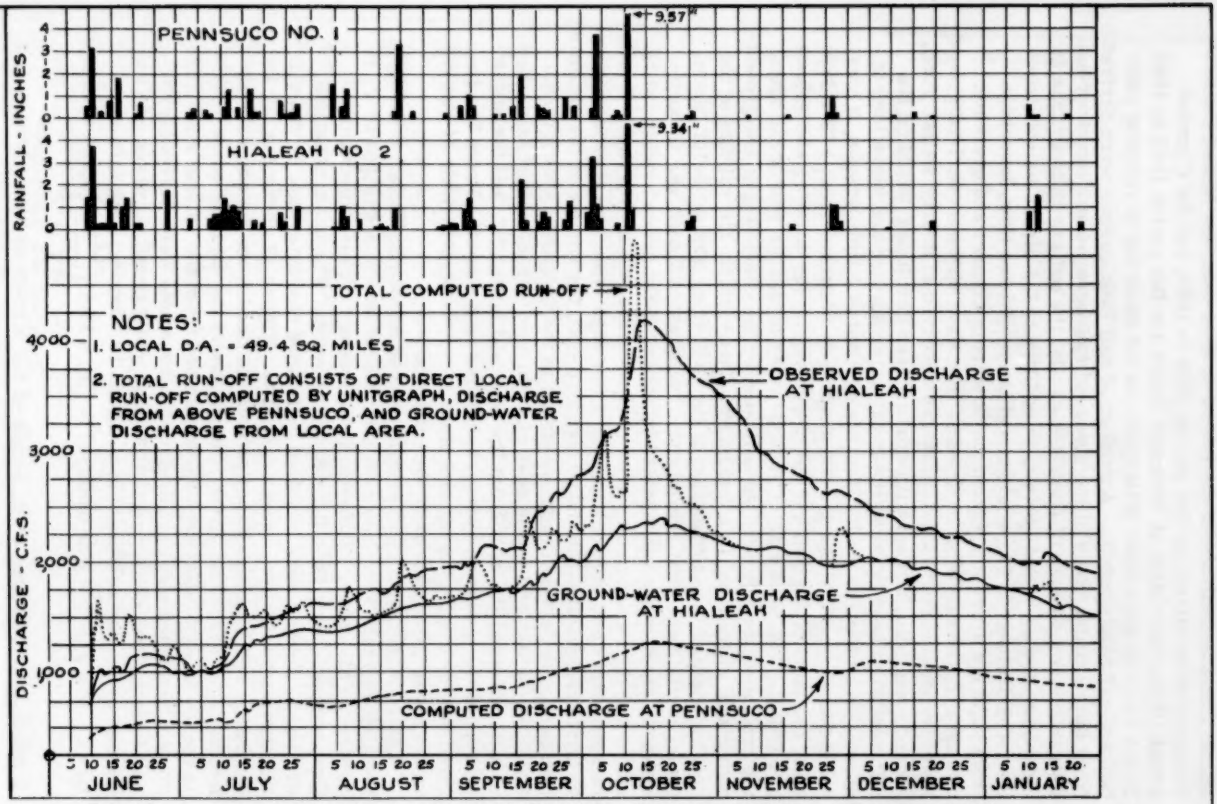


FIG. 18. REPRODUCTION OF 1947 FLOOD - MIAMI CANAL AT HIALEAH

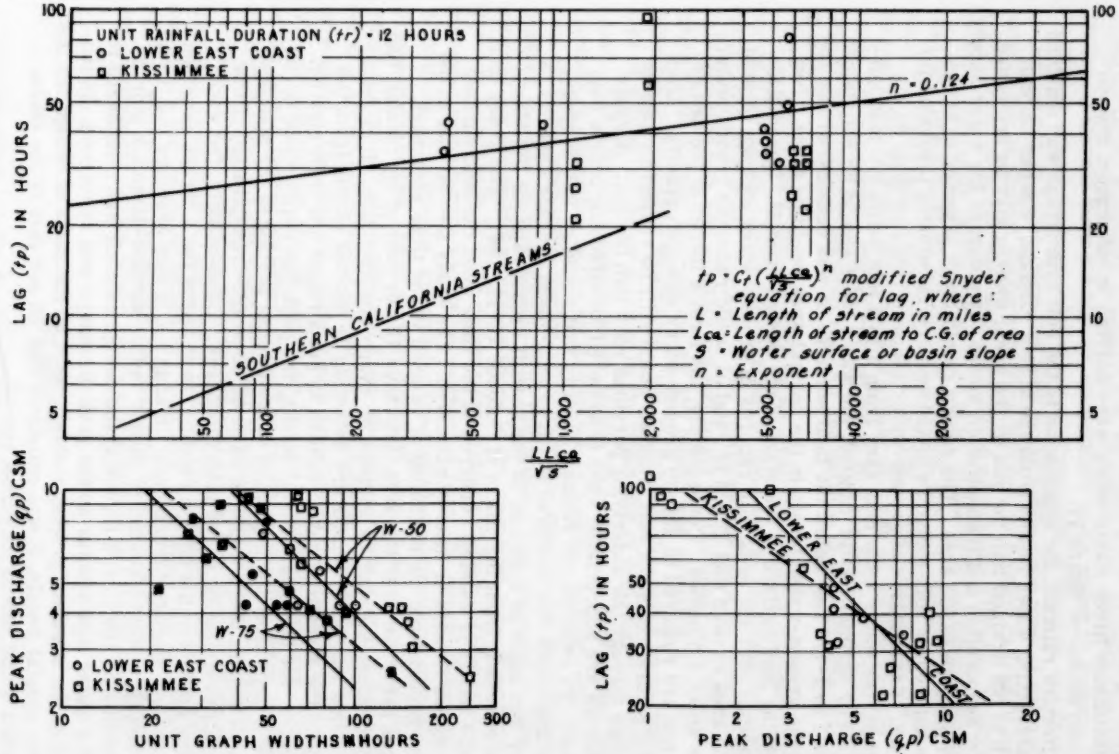

UNIT RAINFALL DURATION (tr) = 12 HOURS
o LOWER EAST COAST
□ KISSIMMEE
n = 0.124
SOUTHERN CALIFORNIA STREAMS
tp = Ct (LLca/√S)^n modified Snyder equation for lag, where:
L = Length of stream in miles
Lca = Length of stream to C.G. of area
S = Water surface or basin slope
n = Exponent
LAG (tp) IN HOURS
LLca/√S
PEAK DISCHARGE (qp) CSM
W-30
W-75
o LOWER EAST COAST
□ KISSIMMEE
UNIT GRAPH WIDTHS IN HOURS
KISSIMMEE
LOWER EAST COAST
PEAK DISCHARGE (qp) CSM

FIG. 19. SYNTHETIC UNIT GRAPH RELATIONS

was used. Figure 19 also shows the derived values for Snyder's coefficient 640 C_p and the width value of the unit hydrograph at discharges corresponding to 50 per cent and 75 per cent of the peak discharge. As a matter of interest and comparison, the run-off factors characteristic of Kissimmee River Basin which were derived in subsequent studies are also shown on figure 19.

Effective rainfall, for application to the unit hydrograph was obtained by subtracting water losses from the design rainfall. Excess rainfall which is not drained into the sea by the canal system may be accounted for by evaporation and transpiration losses, by pumpage for water supply, or by seepage to the area. The design rainfall was assumed to occur when antecedent soil-moisture conditions are reasonably favorable for run-off. Examination of ground-water records revealed that, on the average, the water table may vary from 1 to 3 feet below the land surface. For optimum water control, the water table should be maintained about 1 to 1-1/2 feet below the land surface. It was considered that the average ground-water levels in the coastal area would be about 2 feet below the land surface at the start of the design rainfall. Correlation of rainfall over the area with records of ground-water storage located in the area showed that 1 inch of rainfall would raise the ground-water table about 5.6 inches. Consequently, the first 4 inches of the design rainfall are required to satisfy ground-water storage capacity. After initial saturation of the soil, rainfall would still be subject to loss by seepage through the underlying pervious rock into the sea. Seepage quantities are appreciable when considered as extending over a long period. To evaluate the rainfall quantity that would go into seepage, over and above that required to fill ground-water storage capacity, a study was made of a portion of the run-off hydrograph for the Miami area resulting from the storm of October 10-11, 1947. The 2-day total of 10.3 inches of rainfall occurred at the time when the land surface was either flooded or heavily saturated. The study showed that in the 6-day period from the beginning of rainfall to the time when peak stages prevailed over the area, less than 10 per cent of the rainfall had been dissipated either by seepage or evapo-transpiration. It is recognized that run-off in temporary detention or moving slowly from the area to the stream would be subject to evaporation and transpiration. However, for the local coastal canals, the peak discharge would occur about 2 days after the beginning of the intense portion of the standard project storm; there would be little or no evapo-transpiration of that rainfall contributing to the peak discharge. Consequently, the water losses applied to the design rainfall consisted of the 4 inches required for ground-storage capacity and, in addition, it was assumed that 1 inch of rainfall would be needed to satisfy initial surface-detention storage. Accordingly, the first 5 inches of the design rainfall was considered to be the water loss insofar as the peak discharge was concerned. In the case of the standard project rainfall, used as the basis of design for the lower coastal canals, it was estimated that 80 per cent of the storm rainfall would appear as direct run-off.

For Kissimmee River Basin, investigations are currently in progress to evolve generalized criteria on water losses and regimen of run-off.

The general hydrologic equation for a basin is P-Q-L = Δ S, where P represents the supply in the form of precipitation, Q the run-off, L the water losses, and Δ S the change in storage. For all practical considerations, water losses would consist of evaporation and transpiration—seepage to the substrata considered to be negligible. Storage fluctuates continuously and does not always accumulate since water in storage is subject to evapo-transpiration losses. Two kinds of storage are recognized: water in lakes, streams, and in the subsurface zone of saturation designated as ground storage or base storage; and water in transit on the surface or in the root zone designated as surface storage. Studies in the Kissimmee indicate that base flow, or water from ground storage, will average almost 90 per cent of the total run-off. Depletion from base storage takes place over many months in the Kissimmee, the average lag between recharge and center of mass of outflow ranging from 3 to 4 months. Direct run-off from surface storage is less subject to loss; the lag between rainfall and outflow is usually less than 1 month.

The results of studies to date on generalized criteria for water losses in the Kissimmee can be summarized in the general relationships shown on figures 20 and 21. They show the relationships between monthly rainfall minus losses and monthly run-off found for the upper and lower Kissimmee areas. Run-off during any month was assumed to be a function of antecedent discharge, that antecedent discharge being indicative of storage of water already in the basin and of soil-moisture conditions. The average monthly water losses were used as determined and heretofore discussed in the section on water losses. Monthly run-off was obtained from gage-station records and corrected for base storage—surface storage in most cases being negligible. Any increase in base storage for the month should be added to the recorded run-off and conversely a decrease in base storage signifying withdrawal from original ground-water storage should be subtracted from the recorded run-off. With those adjustments, run-off for the concurrent causative rainfall is properly evaluated. Base storage amounts used in adjustment of the recorded run-off were obtained from storage-outflow curves determined from analysis of the recession of the hydrographs following the orthodox procedure. The plotting points which determined the shape of the rainfall-run-off curves are not shown on figures 20 and 21; however, most of the points plotted satisfactorily. The rainfall-run-off curves can be used as a basis for determining water losses to be applied to design rainfall. Further studies in progress will refine the results obtained thus far. In addition to using base flow as the parameter of antecedent conditions for the rainfall-run-off relations, parameters of antecedent rainfall which occurred during various preceding periods and parameters of ground-water levels where gages are available are being investigated.

SUMMARY

The foregoing briefly describes the physical characteristics and drainage pattern of the Central and Southern Florida Project area comprising some 15,000 square miles. Run-off characteristics are described

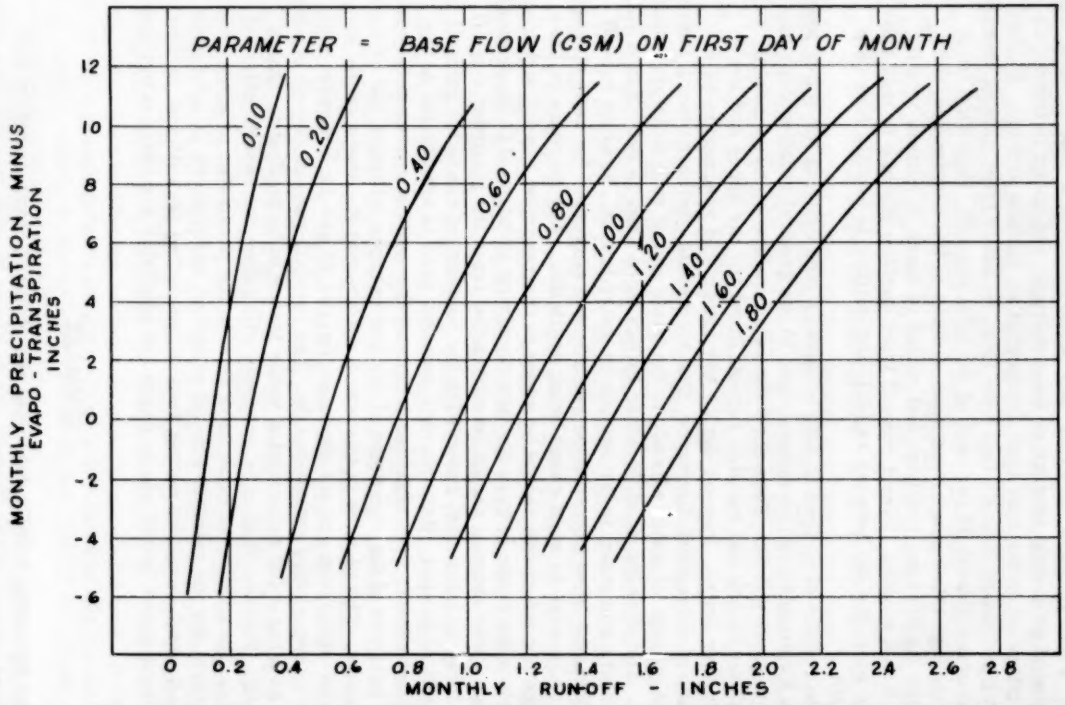


FIG. 20. RAINFALL - RUN-OFF RELATION, UPPER KISSIMMEE AREA

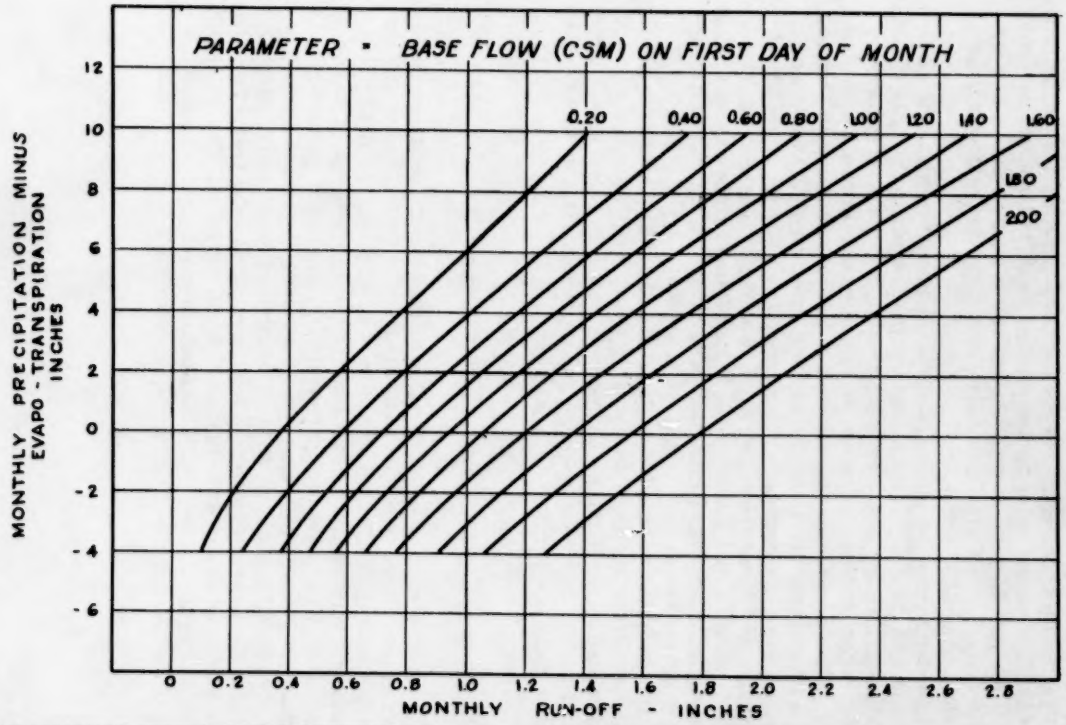


FIG. 21. RAINFALL-RUN-OFF RELATION, LOWER KISSIMMEE AREA

for the principal drainage subdivisions and the records show that annual run-off has ranged from a minimum of about 2 inches in the Kissimmee Basin to a maximum of about 31 inches in the Everglades area. The normal annual run-off has varied from 7 inches in the upper portion of the Kissimmee to about 11 inches in the upper St. Johns Basin. About 50 per cent of the annual run-off occurs during the 4-month period, September through December.

Practically all water losses consist of evaporation and transpiration losses. The annual water losses average about 43 inches in the project area. Generally, a greater percentage of the rainfall is lost to evapotranspiration in the Kissimmee area than in the Everglades region south of Lake Okeechobee.

In order to provide adequate hydrologic basis for studies in connection with the design of structural works, regulation of Lake Okeechobee and structures contained in the project, and the determination of water supply and its utilization, an extensive water-level and streamflow gaging program is concentrated in central and southern Florida. Altogether, there are about 160 surface water gages in the region, most of which are automatic recording gages. For the collection of ground-water levels there are about 70 automatic gages in addition to numerous wells maintained by the United States Geological Survey and various local agencies from which periodic measurements of groundwater stages are made.

As a hydrologic basis for design of the lower east coast canals, the unit hydrograph approach was used. For the Basis of design of canals and related works in the Kissimmee and Upper St. Johns areas, investigations are in progress to evolve generalized criteria on water losses and regimen of run-off.

ACKNOWLEDGMENTS

A major portion of the material presented and the analyses thereof were accomplished in the Jacksonville District Office, Corps of Engineers, under the general supervision of H. A. Scott, M., ASCE; Chief, Planning and Reports Branch. Appreciation to the Corps of Engineers is acknowledged in granting permission for the use of the material. In addition, a valuable reference was provided by the United States Geological Survey Bulletin on Water Resources of Southeastern Florida, Chapter XI, General Hydrologic Analyses, dated July, 1945. The writer also wishes to acknowledge the aid of W. L. Lockwood, Jun. M., ASCE, in preparing the exhibits, C. T. Chambliss in editing the manuscript and Louise W. Horton in typing the manuscript.